

Chapter 1

THE GRAVITY OF THE SITUATION

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Prolonged exposure in environment can lead to significant mass, cardiovascular and sensory-and hormonal changes. These weightlessness present a formidable exploration of space, particularly for times of several months or more, Countermeasures that address each separately show only limited remedy for this situation is artificial all these systems across the board.

Figure 1-01. Astronauts returning from long-difficulty standing upright and moving NASA.

1 WHY ARTIFICIAL

Ongoing manned spaceflight on preparing for future human Mars. For such missions of several years' duration, Mars crews are at risk of catastrophic consequences should the systems that provide adequate air, water, food, and thermal control fail. Beyond that, space travelers will face serious health and/or safety risks resulting from radiation exposure en route and on some extraterrestrial surfaces, behavioral issues associated with the prolonged isolation and confinement, and severe physiological deconditioning due to *weightlessness*¹.

Mitigating the harmful effects of prolonged exposure to the space radiation and weightlessness is one the most significant challenges that must be addressed to realize the long-duration exploration missions currently envisioned. Given the fact that the astronaut explorers who will undertake these missions will be exposed to these deleterious effects for up to several years while they travel to and from Mars, it is of extreme importance that effective *countermeasures*² are identified, developed, tested, and proven prior to undertaking such challenging missions.

¹ *Weightlessness* is the experience (by people and objects) during freefall, of having zero-g force (0 g) or zero apparent weight. This condition is also known as microgravity, since weightlessness in a spaceship is not perfect.

² In a military application, *countermeasures* are systems designed to prevent weapons from acquiring and/or destroying a target. By analogy, in space medicine, countermeasures are systems (mechanical, pharmacological, procedural) designed to neutralize the hazards of the space environment for astronauts' health and performance.

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duration space missions have around. Photo courtesy of

GRAVITY?

efforts are now focused interplanetary missions to

Without the protection of the atmosphere astronauts are exposed to high levels of radiation through a steady flux of cosmic particles. A year in even low-Earth orbit results in a dose of radiation 10 times that of the annual dose on Earth. Experts predict that the dose of radiation received during a 30 months journey to Mars will be about 1,000 times that of the annual dose on Earth, resulting in a high risk of astronauts developing chromosomal aberrations in blood lymphocytes and cancer later in their life. Protective shielding and protective drugs may lower the risks to astronauts to an acceptable level (Cucunotta *et al.* 2001).

More immediate physical effects are those induced by prolonged exposure to weightlessness. These include the loss of bone density, muscle mass, and red blood cells, cardiovascular, circulatory, and sensory-motor deconditioning, and changes in the immune system (Figure 1-02). These effects have been noted in astronauts and cosmonauts exposed to weightlessness for durations of significantly less length than those that will be experienced by future explorers of Mars. Body changes that occur after entering microgravity represent normal homeostatic responses to a new environment. The body's control systems recognize the lack of gravity and begin to adapt to this unique situation, not realizing that the ultimate plan is to return to normal gravity after a transient visit to microgravity. While such reactions by the body may be completely appropriate in the microgravity environment of flight, they are indeed quite inappropriate for arrival on the surface of another planet or for the return to Earth (see Figure 1-01).

Space biomedical researchers have been working for many years to develop countermeasures to reduce or eliminate the deconditioning associated with prolonged weightlessness. Despite these countermeasures, most astronauts experience problems with balance, orientation, and fainting in the first few days after landing. They also risk muscle tears and bone fractures and therefore must exercise an added degree of caution during their recovery period (White and Arvener 2001).

Given that the purpose of a human mission to Mars is not to go there and simply survive, more effective countermeasures or combination of countermeasures must be developed to address the effects of long-term exposure to microgravity. Astronauts arriving at Mars in a weakened physical condition with compromised immune systems who can't manage to ambulate would hardly be able to successfully execute an exploration mission. They would be at risk in the event of a bone fracture, alterations in the heart's rhythm, development of renal stones, or sensory-motor performance failure during piloting, extra-vehicular activity, or remote guidance tasks. Until the problems associated with microgravity exposure are overcome, such missions cannot be seriously considered.

A number of different countermeasures have been employed in an attempt to mitigate the effects of human exposure to microgravity, generally aiming to stimulate a particular physiological system. Exercise workouts stimulate muscles (and to a lesser extent bones and the cardiopulmonary function), while fluid loading countermeasures target the circulatory responses. While these countermeasures have demonstrated only limited success, they are nonetheless the microgravity countermeasures primarily used on board the ISS and the Space Shuttle (Sawin *et al.* 1998)

Artificial gravity is the simulation of the pull of gravity aboard a manned spacecraft by the steady rotation or linear acceleration of all or part of the vehicle (Stone 1973). Artificial gravity represents an alternative approach to addressing the problems of microgravity-induced effects on the human body. Rather than addressing each individual system in a piecemeal fashion, which is only valid if the principle of superposition holds for the combined effect of these interacting subsystems, artificial gravity stimulates all of the physiological systems simultaneously by reproducing the normal Earth gravitational environment. All physical and physiological systems are challenged. Bones are stressed, antigravity muscles are called into action, the otoliths of the vestibular system are stimulated in a manner similar to that on Earth, and the cardiovascular system is similarly stressed. Obviously, artificial gravity cannot address all of the problems associated with long duration spaceflight, in particular that of radiation exposure, altered day/night cycles, and the attendant psychological issues that will no doubt arise from extended confinement and isolation. It does, however, offer a countermeasure with the possibility to address the debilitating and potentially fatal problems of bone loss, cardiovascular deconditioning, muscle weakening, sensory-motor and neurovestibular disturbances, and regulatory disorders. Because artificial

gravity addresses all such systems across the board, it can be considered as an integrated countermeasure (Clément and Pavy-Le Traon 2004).

Figure 1-02. The known adverse affects on human beings of long-term stays in microgravity include bone demineralization, muscle atrophy, and reduction in heart size and plasma volume.

2 MARS MISSION SCENARIO

Mars is the first nearby world that Earthlings will eventually visit. With its recognizable four seasons, clouds, polar ice caps, mountains, dry riverbeds, and dormant volcanoes, Mars is the most Earth-like planet in our solar system, and it has the greatest potential for human habitation. Although it has a very cold, dry climate, surface temperatures at the equator can reach 26°C during the summer.

Scientists believe that there were once similar conditions on Mars and Earth billions of years ago. Data from past Mars missions suggest that the planet once had a warmer, wetter climate and abundant liquid water (lakes, rivers, and even oceans) during its early history. A detailed exploration of Mars would give us insights into the past and future of our planet. We might also learn whether Mars could sustain self-sufficient colonies that might prove to be a lifeboat for humanity's survival in the event of a distant future global calamity. Finally, exploring the planet could create new commercial opportunities and sources of income.

Robotic explorations have already made a detailed study of the planet, found vital sources of water, returned soil samples to Earth, and located the best landing sites. The Mars Exploration Rovers *Opportunity* and *Spirit* are exploring small patches of Mars on opposite sides of the planet. Other missions by NASA and ESA are set to land on various locations of Mars and feature mobile or stationary craft with robotic arm for exploration. These little robots are amazing pieces of engineering and have a lot of discoveries left to go. But they have limitations. It took 56 days for *Opportunity* to explore a 20-meter crater and a year for *Spirit* to travel two kilometers, something an astronaut could perform in a couple of hours.

Although robots will always be necessary, humans could go a little further, wonder what's over the horizon, and explore what the rovers might not reach. Once on the surface, the astronauts will drive for kilometers across the planet's diverse terrain in advanced-type roving vehicles equipped with specialized tools, drills, and analytical instruments. Much of their time will be spent searching for water and past and present evidence of Martian life forms, and conducting a wide range of scientific activities that cannot be accomplished by robotic exploration.

The astronauts must also be shielded from harmful radiation while traveling in their spacecraft and when on the Red Planet's surface. And because the gravity on Mars is only 0.38 g, it is possible that this is not sufficient for counteracting the detrimental effects of microgravity on their body functions experienced during the journey en route to Mars. Their survival in the inhospitable environment will be totally dependent on their combined expertise, specialized skills, and available equipment and countermeasures. When unexpected problems and challenges arise, as they undoubtedly will, the astronauts will have to solve them with little or no help from Earth. Even their radio communications with mission controllers will be difficult because of the time delay between Mars and Earth. Depending on Mars's distance from Earth, which can vary by as much as 320 million km, radio signals from the planet can take anywhere from 4 minutes to 21 minutes to reach Earth.

No one knows how many billions of dollars a human mission to Mars will eventually cost, and the enormous financial burden will have to be shared by other nations. The epic endeavor will be far more dangerous and technically difficult to accomplish than the human missions to the Moon over four decades ago. The Moon was only 350,000 km compared to a 75-million-km voyage to Mars. If an Apollo 13-type disaster were to happen, the astronauts wouldn't be able to return again to Earth.

Exploration and curiosity are in our blood, and they will eventually overcome the challenge of sending humans to Mars for a lengthy stay and then returning them safely to Earth. The underwater world would not have been so appealing without the visionary human touch of Jacques Cousteau. Thanks to the

vision of advocates for human Mars missions, realistic scenarios have been proposed. Since Wernher von Braun first sketched out his *Mars Project* in 1953, a succession of designs and human mission profiles were seriously studied in the United States and the Soviet Union/Russia. Comprehensive reviews of Mars expeditions projects are available on the Internet (<http://www.astronautix.com/craftfam/martions.htm>, retrieved 21 April 2005) and in Portree (2001). The most recent studies of potential Mars mission scenarios include the Paine's Report on *Pioneering the Space Frontier* (Paine 1986), Ride's Report of a *Mars Exploration Plan* (1987), NASA 90-Day Study Mission (Cohen 1989), NASA *Mars Evolution and Space Exploration Initiative* studies (Stafford 1991), Robert Zubrin's *Mars Direct* approach (Zubrin 1991), NASA's *Design Reference Missions* (Hoffman and Kaplan 1997), and the latest NASA's *Vision for Space Exploration* (2004) and ESA's *Aurora Programme* (Bonnet and Swings 2004).

Due to the laws of physics and astronomy, proposed scenarios for human missions to Mars have fallen into two categories: conjunction-class and opposition-class. Low speed transits and a long, roughly 500-day, stay on Mars characterize *conjunction-class* missions before returning to Earth. The long stay on Mars (>50% of the total mission) is required because by the time the ship has arrived at Mars the Earth has proceeded too far around the sun to overtake on a return trip (Figure 1-03).

Opposition-class missions usually entail faster transits, higher delta-V breaking requirements at the target planet, and far shorter stay times on Mars, roughly 30 to 90 days. Typical total trip time will be around 430 days. Often, an opposition-class mission will necessitate the transfer ship crossing inside the orbit of Venus on return in order to catch up to Earth.

As this book is written, a definite timetable for space exploration has not been established. The ultimate time of transit to Mars and back is uncertain because of the undetermined nature of the propulsion system to be employed. Regardless of which mission scenario is chosen, it is going to take many months for people to make the first trips to Mars. Advanced propulsion could cut months off of the travel time, but most experts agree that even the most optimistic plans show approaches using advanced, non-chemical propulsion as being somewhat down the road. The Mars mission scenario we refer to in this book is a conjunction-class type mission, with an Earth-Mars transit time of about six months, Mars surface stay of about 18 months, and a six-month return flight. Hence, a total mission duration of about 30 months. This scenario is not based on any single specific mission architecture. It reflects the best assessment that can be made at this time concerning the possibility of an extraterrestrial venture. Despite these uncertainties, the authors of this book believe their findings and recommendations regarding the most important health issues facing human exploration, and the potential of artificial gravity as a countermeasure, would apply independent of mission scenario.

Figure 1-03. During the past several years, several meetings have reexamined potential Mars mission scenarios (Hoffman 1997). This drawing illustrates one feasible scenario for a human mission to Mars. Total mission time is 905 days away from Earth. This conjunction class mission profile includes a 180-day transit to Mars, a 545-day stay on the surface, and a 180-day return flight.

3 DETRIMENTAL EFFECTS OF WEIGHTLESSNESS

The effects of the space environment on the human body are well documented. For a comprehensive review, the reader is invited to consult other books in this *Space Technology Library* series, including *Space Psychology and Psychiatry* by Kanas and Manzey (2003) and *Fundamentals of Space Medicine* by Clément (2005). Artificial gravity cannot solve the critical problems associated with radiation exposure, isolation, confinement, and reliability of life support systems. However, it can deal with the detrimental effects of long-duration exposure to weightlessness. These effects are reviewed here, with an emphasis on the health and operational issues facing human exploration missions.

3.1 Bone Loss

Bones are living tissue, constantly being strengthened by dietary calcium extracted from the blood and destroyed by returning calcium to the blood for excretion. Bone maintenance requires a compressive

load along the axis of the bone and some high-force impulsive loading. In the absence of these loads that are normally provided by gravity and walking, the major bones that support body weight begin to deteriorate, and a net loss of body calcium occurs, independent of the amount taken in with food or supplements.

The long bones in the legs and the vertebrae in the spine lose mass and strength during prolonged bed rest. Similarly, a loss of bone mineral, and its excretion, are observed in humans during spaceflight. Calcium is lost at a rate of about 1% per month, and the losses are reflected in the density and mass of weight-bearing bones. The rate of calcium loss is not reduced by vigorous exercise. Along with the calcium loss is also a loss of phosphorus. An increase in urinary hydroxyproline (a major component of the protein collagen which provides its strength to the bone) shows that there is a corresponding deterioration of the bone matrix. The increased blood levels of calcium lead to further concern about possible deposition of calcium in kidney or other soft tissue. In weightlessness bone resorption decreases slightly, but bone formation decreases more severely (Lelanc *et al.* 2000).

These changes account for the net decrease in bone mass, especially in the weight-bearing bones, during spaceflight. Unless the process reaches a plateau (which has not been observed during missions up to 14 months in duration), for a spaceflight of two years, a 40% decrease in bone mass might occur. This decrease increases the risk of fracture and possibly severely alters the bone's ability to repair. This bone loss represents a serious danger to astronauts, especially during the stresses of re-entry after a long period of weightlessness.

These changes also continue for up to six months after landing (Vico 2000). Consequently, even after arriving on the Mars surface, astronauts may continue to lose bone mass. If it turns out that Mars gravity of 0.38 g is not enough to prevent further bone mass, astronauts returning from a 30-month mission to Mars might suffer severe osteoporosis. While this bone loss is similar in some ways to osteoporosis observed on Earth, the pharmacological countermeasures used on Earth have no effect upon this phenomenon in space. The effect of exercise in microgravity has yet to be shown to have clear effects upon minimizing this bone loss.

Figure 1-04. Astronaut equipped with a bungee harness and exercising on the treadmill on board the ISS. A vibration isolation system reduces the vibration transferred from the treadmill to the Station structure during exercise. Photo courtesy of NASA.

3.2 Muscle Atrophy

Muscles are adaptable tissues. Increase the load on them by lifting weights or other types of exertion, and they grow larger and stronger. Reduce the load by lying in bed or living in microgravity, and they grow smaller and weaker. When a muscle is loaded, its fibers begin a series of intracellular signaling steps. Genes within the cell nucleus make *ribonucleic acid* (RNA), which synthesizes proteins that make up muscle fiber. Pumping iron activates the expression of these proteins, which accumulate and enlarge the muscle fibers. Microgravity has the opposite effect. It reduces the load that gravity naturally places on muscles, interrupting protein synthesis so that fibers begin to atrophy. This loss of muscle mass contributes to reduced skeletal muscle strength when astronauts return to Earth.

Very significant losses of muscle strength, muscle volume, and total body weight are noted during spaceflight. Muscles that show the largest changes are the major muscle groups in the legs and back that work against Earth's gravity to support body weight.

These changes represent actual breakdown of muscle tissue due to the disuse in weightlessness, and reorganization in the property of the muscle primary constituents, the muscle fibers. Only 14 days in microgravity may atrophy muscle fibers as much as 30% of their size (Edgerton *et al.* 1995). As a result, the muscle generates less force and power. Muscle fibers are of two main types: "slow" fibers that work against gravity to maintain erect posture and "fast" fibers that are involved in rapid, high power movement such as jumping and sprinting. Since slow muscle fibers are the primary anti-gravity, they are affected the most in weightlessness because they are not working against any load. In fact, when subjected to an external load, the slow muscle fibers begin to behave more like fast fibers. Specifically,

they contract more rapidly, making them more adapted for rapid bouts of sprinting than for long-term standing or walking. However, they tire quickly.

Studies reveal that about 15-20% of the slow fibers in a thigh muscle change to fast fibers during a 14-day spaceflight. With longer flights, the degree of fiber switching from slow to fast might increase. A direct consequence of this “reprogramming” of muscle fibers is a decrease in endurance as a function of time in flight, which could have a serious impact on human performance. Also, fast fibers are more vulnerable to injury during contraction. Another matter of concern is the fact animal studies showed that muscle fiber regeneration was less successful in space.

After spaceflight astronauts experience muscle weakness, fatigue, faulty coordination and delayed-onset response. Muscle atrophy also causes soreness as damaged muscles tear while readjusting to Earth’s gravity. Exercise workouts help astronauts fight back. Historically, U.S. and Russian astronauts have relied on aerobic exercises, primarily pedaling a cycle ergometer (an exercise bike) (Figure 1-04) and running while tethered to a treadmill (Figure 1-05). Unfortunately, aerobic exercises are designed to condition the cardiovascular system rather than apply loads systematically to a wide range of muscles. Cycling, for example, applies a good load to the upper leg but not the lower leg or back.

Different types of exercise are required to build strength and resistance to fatigue and injury. Any microgravity exercise routine must maintain not only muscle mass and strength, but also the right mix of proteins to balance fast-twitch muscle power with slow-twitch muscle endurance. On Earth, strength-training programs typically combine isotonic and isometric resistance exercises: high-intensity isotonic motions shorten and lengthen muscles (for example, lifting and lowering a dumbbell), and isometrics fully contract muscles without movement (for example, pushing against a doorway). Theoretically, both types of exercise could potentially reduce muscle atrophy in microgravity (di Prampero *et al.* 1996). Experiments with rats, however, suggest that isometrics may protect slow fibers better than isotonic motions because slow fibers develop very little force during relatively fast isotonic motions.

Yet despite rigorous exercise, astronauts return to Earth shockingly weaker than when they left. Exercise alone has not prevented muscle wasting during spaceflight. The ideal microgravity exercise program therefore remains undefined.

Figure 1-05. Astronaut of the ISS exercising on the cycle ergometer. Photo courtesy of NASA.

3.3 Cardiovascular Deconditioning

The cardiovascular and pulmonary systems supply the body with the oxygen needed for life. On Earth, the heart must work against gravity constantly to push oxygenated blood through the arteries. In space, the lack of gravitational force causes blood and other fluids to shift from the lower to the upper body. This fluid shift towards the head triggers many changes in the cardiovascular system.

Cardiovascular deconditioning begins with the shifting of fluid from the legs and lower trunk to the head and chest immediately upon insertion into orbit. This produces the first symptoms of fullness of the head and associated discomfort on orbit and initiates an early loss of body fluid, including blood plasma. The relative excess of red blood cells is countered by stopping their production in the bone marrow and additionally by destroying young red blood cells.

Long- and short-term studies of humans in space have documented increased heart rate, narrowed pulse pressure, reduced plasma volume, decreased heart chamber volume, and facial edema (Meck *et al.* 2001). Animal studies also indicate that the myocardium may degenerate during microgravity exposure.

The cardiovascular regulating system that acts to maintain adequate blood pressure when we stand up is no longer needed in space and shows signs of deterioration. Neither the fluid loss, with the resulting “space anemia” due to the reduction in red blood cell mass, nor the loss of cardiovascular regulation and tone normally cause any difficulty in orbit. During re-entry and back on Earth, however, the renewed exposure to gravity can cause weakness. Astronauts can feel lightheaded and a drop in blood pressure with standing can lead to fainting. These circulatory deficiencies sometimes remain for weeks after landing (Buckey *et al.* 1996).

In addition, cardiovascular fitness is compromised during flight, resulting in a diminished maximum oxygen consumption capability during exercise. Decreased exercise capacity and orthostatic intolerance are factors that decrease performance during descent from orbit and increase risk during emergency egress from the spacecraft. The mechanisms behind these phenomena remain uncertain, though hypotheses include decreased intravascular volume, increased postflight venous pooling due to structural and reflex vascular changes, and alterations in overall cardiovascular reflex control (Churchill and Bungo 1997).

Unlike the cardiovascular system, no pulmonary system (e.g., ventilation and respiration) problems have been associated with weightlessness per se, and researchers have devoted less attention to its physiology in microgravity. However, lung function can be altered by changes in vascular pressure and volume, and scientists have reported a drop in partial pressure of oxygen in microgravity.

Figure 1-06. The Expedition Three (white shirts), STS-105 (striped shirts), and Expedition Two (gray shirts) crews assemble for a group photo in the Destiny laboratory on the ISS. Photo courtesy of NASA.

3.4 Sensory-Motor Deconditioning

Sensory-motor deconditioning begins in microgravity with the decrease in afferent input to the vestibular (the otolith organs of the inner ear), proprioceptive, and somatosensory systems that are associated with spatial orientation and the control of posture and movement (see Clément and Reschke 1996 for review).

Because the only stimulus to the otoliths in weightlessness is linear acceleration due to translation (but not tilt), considerable reinterpretation of vestibular signals may take place, and new sensory-motor strategies must be developed (Parker *et al.* 1985). A consequence of this process is the common occurrence of space motion sickness early in flight, spatial disorientation throughout the mission (Figure 1-06), and postural disturbances and vertigo after return. Although the incidence of space motion sickness generally vanishes after a few days in space (Davis *et al.* 1988), recurrent episodes have been observed during long-duration missions. Also, the Mir and ISS experience indicate that about 90% of astronauts and cosmonauts suffer from “Mal de Debarquement” following missions lasting several months (Jennings 1997). The symptoms are similar to those of space motion sickness during the flight.

In weightlessness, antigravity muscles are unloaded continuously and antigravity reflexes, utilized in maintaining posture and locomotion on Earth, are inactive or modified. As a result there is a loss of extensor reflexes in space. Sensory information about limb position is not interpreted correctly, and voluntary pointing accuracy and perception of static limb position are impaired. Alteration in the coordination of movements in microgravity is also due to cognitive changes in the mental representation of body (body scheme) and the environment, or to the conservative use of an internal gravity model. Upon return to Earth there is postural imbalance and uncoordinated locomotion that take a long time to readapt after long-duration missions (Paloski *et al.* 1993). After long-duration mission, it is not uncommon for crewmembers to be unable to lift their arms to remove the belt restraint. After flight lasting six months or more, they have to be physically removed from the vehicles on litters (see Figure 1-01).

A prolonged period of postural inactivation and impairment of locomotion would not be acceptable in the event of an emergency during the landing on Mars that demand quick egress from the space vehicle. Moreover, it could also seriously impair the ability of astronauts to accomplish piloting tasks, or even exercising on a treadmill in the Mars gravitational environment. As of today, there are no known countermeasures for such impaired locomotion other than readaptation during exercise in a 1-g environment.

3.5 Regulatory Physiology

The physiology of humans is composed of a totally integrated set of complex subsystems that maintain critical physiological parameters (e.g., temperature, fluid balance, biological rhythms, and electrolyte levels) at relative stable levels, a function called *homeostasis*. Operational observations and spaceflight experiments have demonstrated changes in these physiological parameters and processes. For example, changes in electrolyte balance, blood cell mass, hormone synthesis, and hormone action have been observed during spaceflight.

Body fluid shifts occurring during spaceflight are complicated by the loss of electrolytes (sodium and potassium) that continue throughout the duration of the mission. Hormonal responses seem ineffective in preventing the fluid and electrolyte losses. The extent of these electrolyte losses in long flights is unknown and difficult to predict. Several complications could arise from prolonged electrolyte loss, ranging from dehydration to abnormalities in cardiac function. In fact, the incidence of heart rhythm irregularities seems to increase during long-duration exposure to weightlessness (Fritsch-Yelle *et al.* 1998).

Regulation of body fluid and electrolyte balance is a fundamental homeostatic function. Severe dehydration or loss of sodium and potassium can alter also alter skeletal muscle function, temperature regulation and cellular electrochemical gradients, potentially resulting in circulatory collapse. The regulation of fluid and electrolytes is essential to the ability to respond to physical and emotional stress. The ability of individuals to handle normal as well as emergency procedures after a Mars landing may be severely compromised by a reduction in plasma volume and potassium levels, despite the saline loading taken in an effort to restore plasma volume. At this point, it is not clear just what are the relative contributions of hormones and reflexes in controlling fluid balance.

The loss of red blood cell mass described above undoubtedly contributes to orthostatic intolerance and decreased postflight exercise capacity. While the primary cause appears to be the influence of microgravity itself, the etiology is probably multi-factorial, including influences such as hypokinesia and hypodynamia, bone demineralization, and remodeling, muscle atrophy, altered hemodynamics, modified oxygen demand or oxygen carrying capacity, and nutritional and metabolic disturbances which in turn may be due to microgravity. Regardless of the duration of the spaceflight, restoration of the lost blood cell mass can require four to six weeks following return to Earth. Although this spaceflight-induced anemia does not appear to compromise the health and performance of astronauts during or after flight, in-flight illnesses or injuries could alter cardiovascular and respiratory requirements to the extent that the reduction in blood cell mass could cause a problem.

White blood cells, which help the immune system identify and destroy external or internal pathogens, also appear to experience a reduction in number in microgravity. Pre- and postflight measurements have demonstrated that spaceflight causes a suppression of the cell-mediated immune system, reducing the ability to fight infection. Immune system function returns to preflight levels within approximately 30 days after return to Earth. Due to limited in-flight data, we do not know whether in-flight levels stabilize at a new depressed spaceflight homeostatic level or continue to decline throughout the flight, and whether recovery will occur after extended duration missions (Taylor 1993).

Although data regarding the detailed responses of the neuroendocrine, hematological, and immune systems to extended spaceflight are limited, it is clear that countermeasures are required. These countermeasures include pharmacological, dietary, chemical, and behavioral manipulations (NASA Advisory Council 1992).

Figure 1-07. The Lower Body Negative Pressure (LBNP) device encloses the lower abdomen and lower extremities to maintain a controlled pressure differential below ambient. This causes the intravascular blood volume to shift towards the lower extremities in microgravity, in a manner similar to the orthostatic load caused by assuming an upright posture in Earth gravity. Drawing by Philippe Tazuin (SCOM, Toulouse).

3.6 Human Factors

Human factors problems also arise in weightlessness, including the constant need for hand or foot restraints for stabilization and the possibility of disorientation within a spacecraft. Waste management, fluid handling, food preparation, and hygiene are but a few of the human factors issues present in weightless operations.

The design of workstations and computers must take into account these differences in stature, posture, biomechanics, and strength. But all the new orientations that weightlessness offers cannot be taken into account. For example, what if the crewmember floats over to the workstation upside down? How should displays and controls be designed so that procedures are not performed backward? (see [Figure 1-06](#)).

In orbit, feet are nearly useless appendages after an initial kickoff, with motion controlled mostly by using the fingertips. Pushing on a toggle switch is more likely to result in rotating the operator's human body than in repositioning the switch unless the operator is restrained. Mobility aids and force restraints are essential in reducing bruises among people moving and stopping in space. In partial gravity environments, such as on Mars or lunar surfaces, moving from one place to another is very different from the same activities on Earth. Video sequences of humans on the Moon show that they sort of bounce around. Space suits and tools have to be designed to take into account the way human behavior changes in space.

Natural convection currents do not act without a gravity field, and so hot air does not rise. If an astronaut wants to breathe fresh oxygen in every breath, there have to be fans to circulate the air. The heat from an electrical component such as a laptop does not move away with the air, and so energy must be used for active cooling of every item that dissipates heat, including the human. The confined cabin of a spacecraft limits the range and exercise of human senses and perceptions. The isolation from colleagues, family, and friends can alter social relationships, expectations, and support structures (Kanas and Manzey 2003). The hostility of the external space environment and the inherent risk of spaceflight add stress to everyday tasks. Controlling tele-operated robots or programming automated machines leaves little room for error, takes a lot of time, and requires special skills. A mistake or inattention can quickly result in death or mission failure and consequently everything becomes much more important.

The nature of space combined with the new human-designed environments and tools for living and working in space impact the ways in which people do things. Solving cognitive problems, meeting unexpected challenges, maintaining safety, staying attentive and motivated on long, boring flights from planet to planet, and maintaining teamwork, family ties, and a healthy personality are all aspects of the interaction between a human and the designed environment. This is without counting the fact that sleep and circadian rhythms are also altered during spaceflight (Gündel *et al.* 1997).

Finally, weightlessness also complicates the design and operation of life support systems for human missions, especially for the management of fluids and heat transfer. Since the components of life support systems (e.g., pumps, fluid/air condensers, separators, sublimators) are extensively tested in a 1-g environment, prediction of component behavior and subsequent optimization of the system would become more easy, should artificial gravity be present inside the spacecraft. An artificial gravity design would extend to such performance qualities such as simplicity, reliability, safety, and maintainability (National Research Council 2000).

4 ACTIVITIES ON MARS SURFACE

Being able to function on Mars after a long space trip is of paramount importance. Not only does the crew have to manage a ship as it enters Mars atmosphere and lands, but they also have to deal with the reconfiguration of the ship's systems once it has landed. They also have to be prepared for contingencies after landing, including damage that might occur after a rough landing and assembly of hardware on the surface. There are concerns about the ability of a crew to perform all of these tasks after many months in microgravity.

Studies have already been done on board Space Shuttle missions to allow pilots to practice their landing skills after prolonged stays in space. This is being done to be certain that the ability to orient oneself and fly is not decoupled after long periods in weightlessness. Moreover, as g forces reassert themselves, the amount of blood going to the brain can decrease leading to possible light-headedness, fatigue, or disorientation, something a Mars vehicle pilot cannot afford to experience.

Some lessons can be learned from the ISS experience. For example, in May 2003, due to a software error, the Soyuz that returned the Expedition-6 crew from the ISS followed a steeper descent path. As a result, the crew was subjected to about 8-10 g during re-entry, and they missed their targeted landing site by nearly 400 km. When they opened the hatch, the crewmembers were still strapped into what had become the ceiling. Having come from almost six months in weightlessness, it took the three crewmembers several hours to drag themselves out of the hatch under the oppression of Earth's gravity and erect a folded communications antenna to help the searching planes and helicopters find them. During preflight training, such activity could be performed in just a few minutes.

Given the current state of knowledge, humans arriving on Mars would be in the same bad condition as humans returning to Earth from Mir. The lower Martian gravity would not make much difference. Not having a crew in tip top condition would place landing activities and any post landing surface activities at risk. It is very likely that surface activity on Mars will be rather limited for the first several weeks under even the most optimal circumstances for any crew traveling to Mars in microgravity.

Some astronauts and cosmonauts returning from long-duration spaceflight showed they public that they could stand up upon landing and that they are OK after the experience of living in space for a long time. However, in many cases, this is good for about a few hours, and standing upright at these postflight media events is followed by a 6-week rehabilitation period. Astronauts who actively practice jogging report that after a 16-day spaceflight it takes them several weeks to return to their preflight running capability. When astronaut John Blaha came back from Mir he told the press that he was a "basket case" and that he could not move.

Life on the way to and from Mars is only part of the issues facing Mars mission planners. The space suits to be used on the surface of Mars need to be vastly more attuned to human ergonomics than any currently in existence. Space suits are self-contained spacecraft. Regardless of where you use a space suit, each motion works against the suit's attempt to retain a certain shape while under pressure. Working in a pressurized space suit is difficult, especially for the hands. The suits used in microgravity do not have to contend with prolonged human movement across the surface of a planet. The suits needed for Mars will.

Advanced surface space suits also need to be developed. The suits designed for use on the Apollo missions, while able to allow the crew to perform their tasks, were eventually rendered useless by the end of their brief usage on the Moon. Apollo-17 astronaut Jack Schmitt spoke of how the lunar dust had managed to work its ways into all of the suits joints such that they did not function at the end of his third spacewalk. The space suits to be used on Mars need to be designed for as many as 300 trips across the surface. These trips will last for many hours and will require the users of the suits to perform a wide array of movements. Current Mars suits designs exhaust their wearers after 10 to 15 minutes of use. The suits also need to be designed for routine maintenance on Mars by the crew, not a contractor back on Earth.

Figure 1-08. This photograph of the mid-deck of the Space Shuttle configured for return to Earth shows the three ISS crewmembers in their recumbent seats (right) by comparison with the upright seat of the Shuttle crewmembers (left). Photo courtesy of NASA.

4 CURRENT COUNTERMEASURES

Countermeasures refer to the application of procedures or therapeutic (physical, chemical, biological, or psychological) means to maintain physiological balance, health, physical fitness, and mission performance, reduce risk, and improve the safety of human spaceflight. The countermeasures typically aim at preventing, mitigating, or minimizing the effect of adverse or harmful agents on the crew.

This chapter reviews the countermeasures currently used to moderate the effects of microgravity conditions during space missions, including the constraint they impose on the crewmembers and the timeline.

Space biomedical researchers have been working for many years to develop countermeasures to reduce or eliminate the deconditioning associated with prolonged weightlessness. Some procedures are utilized before the flight, such as medical screening and selecting new astronaut candidates, prescribing individualized exercise programs, or providing quarantine just prior to launch in order to limit pathogens access to flight crew. Other countermeasures are utilized during the flight, such the administration of drug and exercising on various machines workout devices, and during re-entry. However, most of them have been either marginally effective or present a strong inconvenience for the crew or the timeline. After landing, circadian rhythm shifting, hormone replacement, and physical rehabilitation are performed to accelerate the return of crewmembers to normal Earth-based duties.

4.1 In-Flight Countermeasures

In order to not coincide with the episodes of space motion sickness, critical activities, such as space walks, manual docking with other spacecraft, or landing, are not scheduled during the first 2-3 days of a mission. Intramuscular injection of antihistamine promethazine has been quite successful in decreasing the symptoms of space motion sickness in most, but not all, crewmembers. Recent research indicates, however, that this medication can cause deleterious side effects that further degrade human performance and negatively impacts memory, mood, and sleep (Paule *et al.* 2004).

A *Lower Body Negative Pressure* (LBNP) system is a device that can be used by the end of a mission for predicting which astronauts will be more susceptible to postflight orthostatic intolerance (Figure 1-07). This device provides a rapid decompression from ambient pressure to -60 mmHg^3 and therefore similar effects to postflight orthostatic intolerance can occur. Slower or constant decompression regimes can then be applied to recondition the system for Earth's gravity. There are, however, significant inter- and intra-individual differences in the responses to in-flight LBNP tests, which make it difficult to use as a predictive tool (Arbeille *et al.* 1997).

Another countermeasure used for compensating for the loss of fluid is by ingesting about one liter of water or juice and eight salt tablets about one hour before leaving orbit. This fluid loading protocol produces one liter of isotonic saline in the digestive track, which then leads to absorption and subsequent increase in plasma volume. This technique proved effective for short-duration missions by reducing the occurrence or severity of postflight orthostatic intolerance. However, the effectiveness of fluid loading is reduced with longer time in orbit. It is suspected that factors other than cardiovascular deconditioning become more important on longer flights with regard to causing orthostatic intolerance.

In the critical period of re-entry and landing, Shuttle astronauts routinely may wear anti-gravity suits. These suits contain balloon-like pressure bladders in the pants, which can be inflated with air by the astronaut. When the astronauts inflate the bladders in their pants, the bladder presses against the legs, forcing body fluid into the upper body. This helps the heart to pump the blood more efficiently by pushing the blood out of the lower extremities. The Russians wrap the lower body tightly with elastic strapping to achieve the same effect as the anti-gravity suit.

Anyone who has been on orbit for more than 30 days is required to be returned to Earth in the supine position (hence receiving gravito-inertial forces along the $+G_x$ direction⁴) to reduce the risk of orthostatic intolerance during re-entry and landing. The Space Shuttle is equipped with recumbent seats for returning long-duration crewmembers from the ISS (Figure 1-08). There is, however, a concern that a

³ Millimeter of mercury (mmHg) is a non-SI unit of pressure, but it remains a common unit for the measurement of blood and gas pressure. It is the atmospheric pressure that supports a column of mercury 1 millimeter high. $1\text{ mmHg} = 133.32\text{ Pa}$ or $1.3158 \times 10^{-3}\text{ atm}$.

⁴ Throughout this book, G_x , G_y , G_z indicate the direction of the gravito-inertial force vector along the body x-, y-, or z-axis, respectively. For the definition of the body axes and the sign convention, see Figure 2-02. The gravity level unit is indicated by the letter g , e.g., “the subject received 2 g at the feet in the $+G_z$ direction”.

long-duration flight crewmember could probably not egress from the recumbent seat system without some assistance.

Figure 1-09. Left: Astronaut wearing squat harness pads performs knee-bends using the Interim Resistive Exercise Device (IRED) equipment on board the ISS. Right: He is using the “short bar” of the IRED to perform upper body strengthening pull-ups. Photo courtesy of NASA.

Although its effects on orthostatic tolerance are still unknown, an in-flight aerobic exercise program is done in conjunction with the exercise for counteracting muscle atrophy. The ISS crews exercise 2½ hours per day for three days, with some optional change on the fourth day. Several exercise devices are available, including a treadmill to preserve aerobic power, a cycle ergometer to preserve aerobic capacity, a resistive exercise device to preserve muscle strength, and handgrip equipment to preserve hand strength for extra-vehicular activity.

The treadmill may be used for walking, running, and doing knee bends and resistive exercise (see Figure 1-04). Loads are exerted on the subject by restraint harnesses and bungee cords to simulate, as closely as possible, normal gravity skeletal loading during exercise. There are two modes of operation: (a) the motorized (active) mode provides astronauts with speed control adjustable from 0-16 km/h; and (b) the non-motorized mode allows the astronaut to drive the tread belt with variable mechanical resistance without the use of a motor. The treadmill can be used as an ambulating trainer, endurance exercise of postural musculature, high impact skeletal loading for bone maintenance, and aerobic exercise for cardiac training.

The cycle ergometer provides workload variable between 25 and 350 watts, driven by the hands or feet, which is controlled by manual or computer adjustment (see Figure 1-05). It operates with the subject seated or supine, and provides time-synchronized data compatible with other complementary analyses. The cycle ergometer is used as an aerobic and anaerobic exercise countermeasure, for the maintenance of lower body musculature endurance and for arm exercise training in preparation for extravehicular activity.

The *Interim Resistive Exercise Device* (IRED) includes a series of human-machine interface devices (e.g., handgrips, straps, curl bars, ankle cuffs, squat harness, etc.) that permit a variety of exercises to be performed by the astronauts (Figure 1-09). Cables on each side of shoulder straps are connected to two canisters, each containing a series of “flex packs” that can be dialed in sequentially to add greater resistance to the cables. The device provides eccentric and concentric contraction through a full range of motion of various exercises (Table 1-01). The IRED is used as training for muscle strength and endurance of all major muscle groups, to maintain skeletal muscle mass and volume, and to provide high-strain skeletal loading for bone maintenance.

| <i>Day 1</i> | <i>Day 2</i> | <i>Day 3</i> |
|-------------------------------|-------------------------|-------------------------------|
| <i>Deadlifts</i> | <i>Shoulder presses</i> | <i>Squats</i> |
| <i>Bent-over rows</i> | <i>Rear raises</i> | <i>Heel raises</i> |
| <i>Straight leg deadlifts</i> | <i>Front raises</i> | <i>Straight leg deadlifts</i> |
| <i>Heel raises</i> | <i>Hip abduction</i> | <i>Bent-over rows</i> |
| | <i>Hip adduction</i> | |

*Table 1-01. Resistive exercise workout recommended daily for the ISS astronauts.
Note that lower body exercises are performed every day.*

While exercising, the Russian cosmonauts sometimes also use thigh constriction cuffs to decrease fluid shift, although real data on the effectiveness of these cuffs are lacking (Herault *et al.* 2000). Further in-flight countermeasures include whole-body elastic loading suits, such as the Russian “Penguin” suit (Figure 1-10). Beside its effect on the cardiovascular system, the elastic bands in the suit also simulate some of the gravitational effects on the musculoskeletal system. Expanders are also used occasionally.

Figure 1-10. The “Penguin” suit. The inside of the suit contains a system of elastic, straps, and buckles that can be used to adjust the fit and tension of the suit. This suit forces the subjects to use his extensor muscles in microgravity to activate venous return. Drawing by Philippe Tauzin (SCOM, Toulouse).

4.2 Research on Countermeasures

The unique environment of spaceflight imposes unique demands on exercise protocols in order to be effective to the uppermost maximum. The effectiveness of a protocol is determined by an adequate compromise among exercise efficacy, ease of performance, subject compliance and the operational demands of spacecraft, i.e., size and weight of equipment, operational time constraints, and minimal environmental disruption. One major problem is that the workout procedures described in the previous section are strenuous, uncomfortable, and excessively time-consuming for many astronauts and cosmonauts.

It is well known that exercise has potential benefits on the cardiovascular, immune, and musculoskeletal systems, and is therefore also potentially beneficial to the vestibular and thermoregulatory problems. However, despite intensive in-flight schedule, the effectiveness of the current exercises for maintaining bone, muscle, and aerobic fitness has not been demonstrated. Furthermore, they have inconsistent effect on sensory-motor adaptive changes and postflight orthostatic hypotension.

This is partly because different types of exercises are required to build muscle strength and resistance to fatigue and injury, and maintain bone integrity. Studies continue to be conducted to address how muscles and bones should be loaded in microgravity in order to prevent these changes (Baldwin *et al.* 1996). In contrast with the extensive studies of the effects of exercise on muscle tissue, the possible bone tissue enhancing effects of exercise are a relatively recent topic. Indirect evidence is continually building up to suggest that there is a relationship between exercise and a decreased degree of osteoporosis.

Some scientists currently believe that bone mass is not only controlled by the high-magnitude, low-frequency strain resulting from the mechanical loads on bones associated with vigorous exercise, but also by low-magnitude and high-frequency strain that the musculature continuously places on bones while sitting or standing. Results of ground-based studies suggest that barely perceptible vibrations may generate enough strain to stimulate bone growth (Rubin *et al.* 2001). If proven valuable for humans, low-level vibrations during spaceflight may offer an alternative for the current, time-consuming astronaut exercise regimes for long-duration space missions.

Metabolic status can also have an effect on the physiological changes, such as bone demineralization and muscle atrophy. For this reason, nutritional countermeasures are believed to be an integral part of newer countermeasure programs (McCormick and Donald 2004). Caloric intake is an option, especially in relation to the energy expended in exercise. Obviously the diet must have the potential for supplying enough calories so that it would not be necessary to break down body tissues to supply the energy being used. However, it seems that increased caloric intake does not spare muscle tissue, and that spaceflight changes their relationship through unknown mechanisms.

Hormones are also major factors in control of synthesis and breakdown of tissue proteins with complex interrelations. One hormone directly involved in tissue synthesis is *growth hormone*; its presence is essential for formation of muscle, bone, and other tissues during development. Other hormones which may be involved in maintaining muscle mass are insulin and testosterone. Reductions in growth hormone and testosterone during spaceflight worsen muscle health. If the opposite is true, augmenting selected hormones may maintain muscle mass in space and on Earth.

Other countermeasure projects are attempting to increase protein synthesis rates with supplements of amino acids for muscle. For bone, studies are looking at biphosphonate compounds that bind to bone crystal and tend to inhibit bone resorption, or the hormone glucose-dependent insulino-tropic peptide, which is involved in insulin production that some bone cells contain.

However, in the case of pharmaceutical countermeasures, changes in the pharmacokinetics of those drugs during spaceflight must be examined. Studies have so far indicated that drug efficacy may

differ in weightlessness. In addition, recent evidence of rapid degradation of pharmaceuticals flown during long-duration missions, putatively due to radiation effects, raises concerns regarding the viability of this type of countermeasure.

Nevertheless, a balance between healthy nutrition, therapeutic measures, drugs, and exercise is likely to provide a better protection. However, although improvements in exercise protocols, changes in diet, or pharmaceutical treatments of individual systems may be of value, they are unlikely to adequately eliminate the full range of physiological deconditioning induced by weightlessness. Also, the urgency for exploration-class countermeasures is compounded by the limited availability of flight resources for performing the validation of a large number of system-specific countermeasure approaches. The surest countermeasure is clearly one that produces a gravito-inertial environment close to that on Earth, also known as artificial gravity.

Figure 1-11. Current knowledge in space medicine is limited to space missions ranging from a few weeks to six months. Virtually nothing is known for missions lasting one year and beyond. Adapted from John Charles (NASA, Houston).

5 ARTIFICIAL GRAVITY: AN INTEGRATED COUNTERMEASURE

To succeed in the near-term goal of a human mission to Mars during the second quarter of this century, the human risks associated with prolonged weightlessness must be mitigated well beyond our current capabilities. Indeed, during nearly 45 years of human spaceflight experience, including numerous long-duration missions, research has not produced any single countermeasure or combination of countermeasures that is completely effective. Current operational countermeasures have not been rigorously validated, and have not fully protected any long-duration (>3 months) crews in low-Earth orbit. Thus, it seems unlikely that they will adequately protect crews journeying to Mars and back over a 30-month period (Figure 1-11).

Using the current countermeasure methods, humans would not be operational after landing on Mars following a six-month journey in weightlessness. Changes in neurovestibular, cardiovascular, musculo-skeletal systems are reversible upon return to normal gravity, but their readaptation can take several weeks. It is not certain that the Mars gravity (0.38 g) will be sufficient for re-adapting these functions while on the Red Planet's surface.

Artificial gravity represents a different approach to the problem of microgravity (or reduced gravity) effects on the human body, as it simply mimics our natural 1-g environment. Not just one physiological system at a time is challenged by artificial gravity, but all body systems simultaneously. Although artificial gravity will not be a panacea for all the human risks of spaceflight (it cannot solve the critical problems associated with radiation exposure, isolation, confinement, and life support systems failures), it does offer significant promise as an effective, efficient multi-system countermeasure against the physiological deconditioning associated with prolonged weightlessness. Virtually all of the identified risks associated with bone loss, cardiovascular deconditioning, muscle weakening, neurovestibular disturbances, space anemia, and immune system deficiency might be alleviated by the appropriate application of artificial gravity. Artificial gravity would also greatly enhance habitability and personal hygiene during extended missions, making it easier for astronauts to carry out activities associated with everyday life. For example, thanks to artificial gravity inside a space vehicle, liquids and particulate matter will “fall” to the floor rather than float around and get in people's eyes or mouths, the toilets could actually flush and accommodate female astronauts better, the galley for cooking and eating will be simpler to design, and no bungees will be required for exercise. In fact, cots, treadmills, and weights could be used. Also, artificial gravity will provide a better environment for medical procedures, especially emergencies like cardiopulmonary resuscitation, surgery, and for maintaining a sterile environment where needed.

The best technique for implementing artificial gravity in space can only be determined after weighing a complex set of trade-offs among vehicle design/engineering costs, mission constraints, countermeasure efficacy and reliability requirements, and vehicle environmental impacts.

For example, from a physiological countermeasure perspective, a good solution might be to provide artificial gravity continuously throughout the mission. The benefits of providing a continuous artificial gravity level will most likely reduce or eliminate physiological deconditioning, improve human factors (e.g., spatial orientation, hygiene, food preparation, work efficiency), medical equipment/operations (e.g., countermeasures, surgery, cardio-pulmonary resuscitation), and habitable environment (e.g., management of liquids and contaminants). However, these benefits would need to be weighted against the risks/uncertainties, which include the engineering challenges (e.g., requirements, design, truss, fluid loops, propulsion), and the human factors and physiological issues which will ultimately result from the deactivation of the artificial gravity once the space vehicle will arrive in the vicinity of Mars. Considering that half of all astronauts require one to three days to adapt to microgravity, a similar period of adaptation when artificial gravity is deactivated is not unreasonable. So, the full set of trade-offs cannot be fully evaluated until after further physiological research and vehicle design estimates have been completed.

Figure 1-12. Illustration of Wernher von Braun's space station concept by artist Chesley Bonestell. This station, made of flexible nylon, would be carried into space by a fully reusable three-stage launch vehicle. Once in space, the station's collapsible nylon body would be inflated much like an automobile tire. The 75-m-wide wheel would rotate to provide artificial gravity. Photo courtesy of NASA.

The design for such a space habitat with continuous artificial gravity would resemble a torus or donut-shaped ring that is about several kilometers in diameter and rotates once per minute to provide Earth-normal gravity on the inside of the outer ring via centrifugal force (Figure 1-12). Another way to achieve Earth-normal gravity is not by constant rotation but by steadily increasing straight-line speed at just the right rate (Figure 1-13).

However, there are several reasons why large-scale rotation or acceleration is unlikely to be used to simulate gravity in the near future. In the case of a manned Mars spacecraft, for example, the structure required would be prohibitively big, massive, and energy-costly to run. An alternative approach for such a mission, and one being explored, is to provide astronauts with a small spinning bed on which they can lie, head near the center and feet pointing out, for an hour or so each day, so that their lower body can be loaded in approximately the same way they would be under normal Earth-gravity. While not expected to be as efficient a solution from a physiological standpoint (in particular due to the gravity gradient effects), it may prove effective, and the engineering costs and design risks might be lower.

Note that the physiological responses to continuous Mars's gravity (0.38 g) exposure are unknown. Indeed, the physiological responses to continuous exposure to anything other than 1 g are unknown. If it turns out that substantial physiological deconditioning occurs at Mars gravity, then artificial gravity may be required to protect crews during long stays on the surface of Mars. The only feasible implementation on a planetary surface would be intermittent artificial gravity.

Figure 1-13. In the cartoon stories of "Tintin: Destination Moon" and "Tintin: Explorers on the Moon" (1953) by Hergé (Casterman, Paris), the nuclear-powered Moon rocket continuously accelerates at 1 g in a straight line, creating artificial gravity inside the spacecraft by a force in the opposite direction of the direction of acceleration. At mid-distance between the Earth and the Moon, the rocket turns around and decelerates, still at 1 g, down to the Moon surface.

However, several research questions remain to be answered before artificial gravity can be effectively utilized on board space vehicles. It is the objective of this book to review these questions and proposed research for finding the answers. A critical question is: What level of acceleration is the minimum required to maintain normal function? We can be reasonably certain that 1 g will suffice, but is it needed? Will 0.5 g do? Or can we avoid deconditioning during the travel to Mars by spinning continuously at a level of 0.38 g to match the gravity on Mars?

We already know that rats, which have been centrifuged during spaceflight, don't show the major deterioration in bone, muscle, and cardiovascular response seen by free-floating animals. But that is only at 1 g. The current ISS plans include a module for a centrifuge to carry up to eight modules for rodents,

fish, and eggs, but will not accommodate the primates which many feel are needed to adequately model human responses.

Intermittent artificial gravity stimulation presents a number of potential advantages. As part of our normal circadian rhythm, the very gravity-dependent processes that result in fluid loss and bone deconditioning are probably turned off during our normal sleeping hours (Vernikos 2004). On the other hand, extended periods of bed rest produce effects on the skeleton, muscles, and cardiovascular system that are similar to those occurring in space. This simulation of spaceflight is made more accurate if the bed rest is conducted with a six-degree head-down tilt to accelerate the shift of fluid toward the head and if the subject lies partially immersed, although dry, in a high-tech waterbed (Figure 1-14).

A combination of short- and long-duration studies in ground centrifuges and slow rotating rooms can be useful in answering many of the key questions concerning the application period, frequency, and intensity of centrifugal force. They will also be useful in determining the seriousness of the problem of dual adaptation to the rotating and non-rotating environments. Importantly, they may shed light on the physiological importance of a gravity gradient across the body if one is to truly proceed with rotators having a radius comparable to the subject's height. These ground gravitational physiology studies are essential for effective use and interpretation of the artificial-gravity prescription to be used in space (Young 1999).

Figure 1-14. Water immersion has been used as an analog for weightlessness by a number of investigators, primarily studying renal and circulatory events. This treatment produces rapid fluid shifts by changes in hydrostatic forces and negative pressure breathing. Subjects in "dry immersion" are protected from water contact by a thin plastic sheet, thus avoiding the problem of skin maceration (Nicogossian and Parker 1982). Drawing Philippe Tausin (SCOM, Toulouse).

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